

IF amplifier stability for the Heterodyne Instrument for FIRST (HIFI)

Michael D. Seiffert^a and ...

^aJet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, USA

ABSTRACT

The Heterodyne Instrument for FIRST (HIFI) is a heterodyne receiver system which has an intermediate frequency (IF) amplifier that will likely exhibit 1/f-type gain fluctuations. Although the level of fluctuation is very small, wideband spectral observations require exceptional stability. Several methodologies for measuring 1/f fluctuations are described along with measurements of three amplifiers. Comparisons are made with previous 1/f measurements of HEMT amplifiers. The implications for HIFI are described.

Keywords: FIRST, HIFI, heterodyne instrument, amplifier stability

1. INTRODUCTION

The ‘Far-Infrared and Submillimeter Telescope’, (FIRST), is the fourth European Space Agency (ESA) cornerstone mission in the current ‘Horizons 2000’ science program.¹ FIRST will be an exciting new space-based observatory that will revolutionize astrophysics in this important wavelength regime. It will allow detailed investigations of the formation and evolution of galaxies in the early universe, the cycling of gas and dust between stars and the interstellar medium, and many others.

One of three instruments, the Heterodyne Instrument for FIRST (HIFI) is designed to provide continuous frequency coverage of the 480 - 1250 GHz range; additional bands cover 1410 - 1910 GHz and 2400 - 2700 GHz. HIFI has the exceptional spectral resolution available with heterodyne receivers and the low system noise achievable with Superconducting-Insulating-Superconducting (SIS) mixers and Hot Electron Bolometer (HEB) mixers.²

HIFI’s high spectral resolution is particularly well suited to the study of molecular and atomic fine structure line emission. Many of the most interesting lines, including those from water and HD, are only accessible from space.

One of the HIFI goals is the observation of [CII] 158 μm emission from the interstellar medium of galaxies. This atomic fine structure line is a primary cooling line and therefore an important physical probe of the physical conditions of the interstellar medium. Observations of this line in highly redshifted galaxies will allow an investigation of the physical properties of galaxies near the time of their formation and also allow the study of their evolution. Because these galaxies will be spatially unresolved, the emission will be broadened by the contribution from many different parts of the galaxy. Observations of very broad lines pose special instrumental challenges, in particular greater stability.

One of the critical items in the receiver chain is the IF amplifier. HIFI has one cryogenically-cooled IF amplifier after each mixer. Low noise in these amplifiers is important in minimizing the overall system temperature of the receiver. Such amplifiers are known to have 1/f - type gain fluctuations,^{3, 4, 5} These fluctuations can adversely affect wide bandwidth observations unless there is some form of sufficiently fast instrument chopping.

Below, we examine the connection between transistor fluctuations and amplifier fluctuations, make predictions for the amplitude vs. frequency for such fluctuations, and make a preliminary attempt to assess the impact on wide bandwidth observations.

E-mail: Michael.D.Seiffert@jpl.nasa.gov

2. MATHEMATICAL DESCRIPTION

There are several useful scaling arguments that we can apply to understand how the gain fluctuations in a single transistor are related to the dimensions of the transistor. We can also relate this to the fluctuations in the amplifier as a whole based on the type and number of devices. We can then relate this to the instrument stability.

Fluctuations in the transconductance of individual HEMTs can lead to gain fluctuations in an amplifier built from these HEMTs,^{3, 4} In order to minimize noise figure, very low noise cryogenic amplifiers typically do not make extensive use of feedback to minimize these fluctuations. We will use a semi-empirical approach to characterize the effect. We can describe the gain fluctuations in an amplifier according to

$$\frac{\Delta G(f)}{G} = \frac{C\sqrt{N_s}}{(A_{\text{gate}}/5\mu\text{m}^2)}. \quad (1)$$

Here, $\Delta G(f)/G$ is the fractional gain fluctuation as a function of post-detection frequency, f . The amplifier is assumed to have N_s stages, each of area A . The constant, C , describes the level of fractional gain fluctuation of individual HEMTs, normalized to a gate area of $5\mu\text{m}^2$ (corresponding to a device with dimensions of $50\mu\text{m} \times 0.1\mu\text{m}$).

For radiometric applications, it is useful to compare the level of gain fluctuations to the white noise level of the system. We'll examine the impact on spectroscopic applications in the next section. First, we define the post-detection frequency at which the gain fluctuations have the same spectral power as white noise as the knee frequency, f_{knee} . We can calculate the equivalent rms noise, ΔT_{equiv} of the gain fluctuation,

$$G\Delta T_{\text{equiv}} = T_{\text{sys}}\Delta G(f), \quad (2)$$

where T_{sys} is the system noise temperature. As we noted above, the knee frequency occurs where the gain fluctuations equal the white noise. To calculate this frequency, we substitute the white noise level,

$$\Delta T_{\text{equiv}} = \frac{T_{\text{sys}}}{\sqrt{\beta/2}}, \quad (3)$$

where β is the RF bandwidth of the system; the units here are $\text{K}/\sqrt{\text{Hz}}$. Substituting Eqn. (3) into Eqn. (2) yields

$$\frac{\Delta G(f_{\text{knee}})}{G} = \frac{1}{\sqrt{\beta/2}}. \quad (4)$$

We can now use Eqn. (1) and solve for f_{knee} ,

$$f_{\text{knee}} = \frac{C^2 N_s \beta}{2(A_{\text{gate}}/5\mu\text{m}^2)}. \quad (5)$$

The knee frequency is useful as an indicator of how fast to chop the instrument for continuum observations. We note that there could well be other important sources of instrument instability.

3. MEASUREMENTS

In order to assess the level of gain fluctuations in IF amplifiers, we have made measurements of two 8-12 GHz amplifiers built by a group at the Centro Astronomica de Yebes, Spain. The first amplifier was built with InP HEMTs from TRW with gate dimensions of $0.1 \times 160\mu\text{m}$. The second was built with InP HEMT devices from ETH with gate dimensions of $0.2 \times 200\mu\text{m}$. Each amplifier consists of two transistor stages.

To measure gain fluctuations, we use the setup depicted in Fig. 1. A synthesized source (HP 8673D) provides a stable signal at 10.000 GHz. This signal is passed to the device under test (DUT) and then detected with a Wiltron detector diode. The synthesized source RF level was adjusted to produce a DC level of -2.00 mV on the detector diode. The diode was sampled at 6250 Hz with a very low noise, high gain data acquisition system. After the time series data is collected, the power spectrum can be computed and compared to the measurement baseline which is established with no device under test. Figure 2 shows the results for the amplifier built with TRW devices. The level of fractional gain fluctuation at 1 Hz is approximately $2.5 \times 10^{-5}/\sqrt{\text{Hz}}$. Figure 3 shows the results of a similar test of

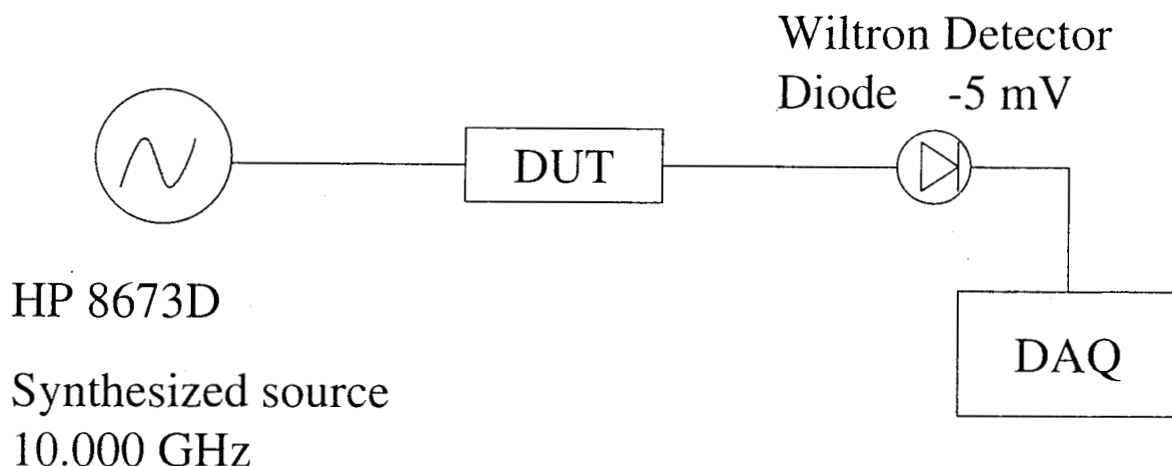


Figure 1. Experimental setup. A synthesized source was used to provide an input signal to the device under test (DUT), in this case, an IF amplifier. Gain fluctuations in the DUT cause fluctuations in the level detected by the detector diode. The RF signal was set so that there was approximately -5 mV on the detector.

an amplifier constructed with the ETH devices. This amplifier appears to have a slightly lower level of gain fluctuation; we'll take the level to be approximately $2.3 \times 10^{-5}/\sqrt{\text{Hz}}$. More data is clearly required to precisely quantify the difference between the two amplifiers. :

The data described above was collected at room temperature. Previous experience with InP HEMTs suggests that at cryogenic temperatures the level of gain fluctuation will increase by a factor of 2 - 3. Taking a factor of 2.5 as typical and using the preceding results with Eqn. (5), we can estimate a knee frequency contributed by the IF amplifier. An important factor in Eqn. (5) is the RF bandwidth. We'll make two estimates using different bandwidths: the full RF bandwidth of 4 GHz in the wide bandwidth receiver mode, and a fiducial bandwidth of 100 MHz. The results are shown in Table 1.

| | RF BANDWIDTH | |
|-------------|--------------|-------|
| | 100 MHz | 4 GHz |
| ETH devices | 0.18 | 7.2 |
| TRW devices | 0.20 | 7.8 |

Table 1. Estimated 1/f knee frequencies for 100 MHz and 4 GHz bandwidths

The 4 GHz bandwidth is appropriate for an observation where the instrument is used as a radiometer in which the entire bandpass is compared between an on-source and off-source position. For such continuum observations, we see that the chop speed should be faster than about x Hz. For observations of broad lines, however, one can

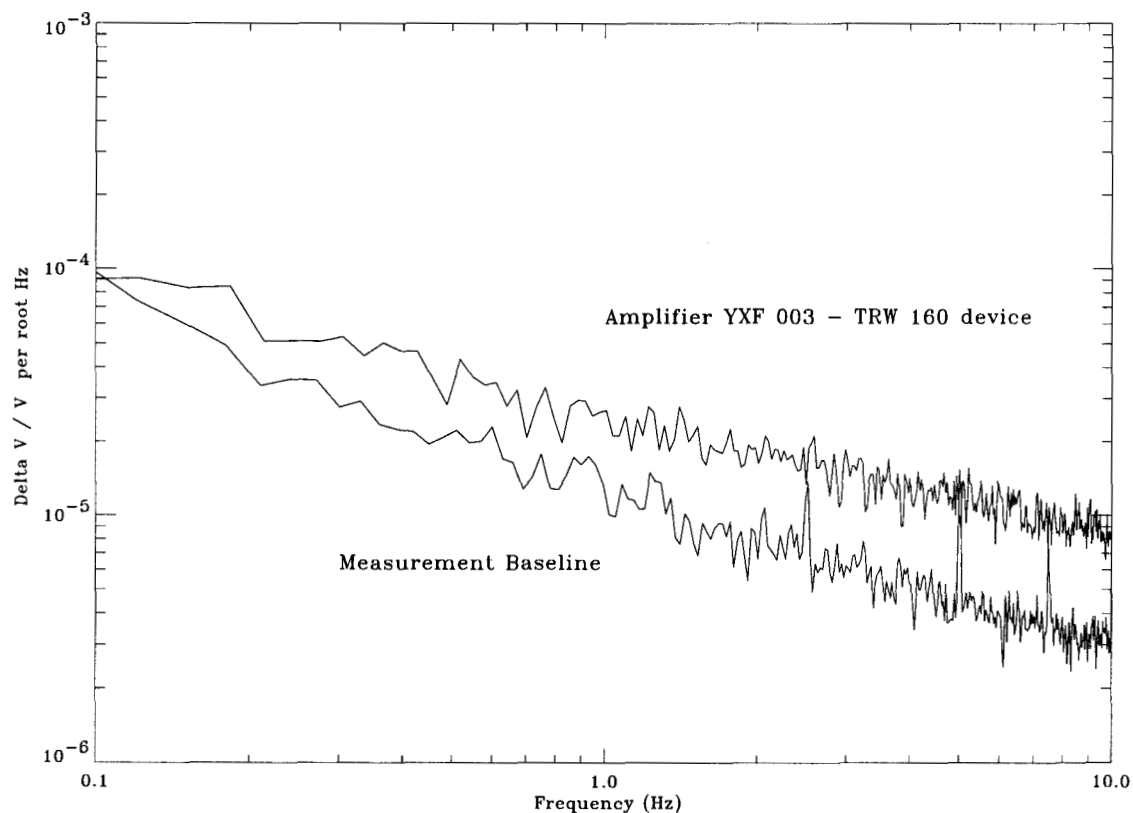


Figure 2. Measurement of amplifier gain fluctuations. The upper curve is the fluctuation level for a two-stage amplifier built with TRW 200 micron gate width devices.

use the part of the RF spectrum that has no line in it as an additional reference for chopping. The effectiveness of this depends upon the bandwidth of the line and the degree to which the gain fluctuations are correlated across the band. This is the subject of the next section.

Again, we stress that the IF amplifier may not be the only source of instability in the receiver system.

The gain fluctuation measurements could have benefited from a better measurement baseline. From previous experience with some of the components, we believe that the synthesized source is the dominant source of fluctuations in the baseline data. A significant improvement may be obtainable with a cavity stabilized, temperature stabilized Gunn oscillator.

4. IMPLICATIONS FOR WIDE BANDWIDTH OBSERVING

We now turn to the implications of the measurements described in the previous section for observing broad spectral lines with HIFI. Of key importance is the degree to which the gain fluctuations are correlated with frequency. If the IF amplifier has gain fluctuations that are perfectly correlated with frequency, then we can easily remove the effect: we simply subtract from the region of spectral interest a nearby signal-free portion of the spectrum. Another way to look at this is that gain fluctuations that are perfectly correlated across frequency produce flat baselines (in the absence of other systematic effects, of course). If the gain fluctuations are not perfectly correlated with frequency, there will be some impact on the baseline.

To assess this impact, we performed the following simulation. The amplifier is assumed to have gain fluctuations that are correlated with frequency according to the curve shown in Figure 4.

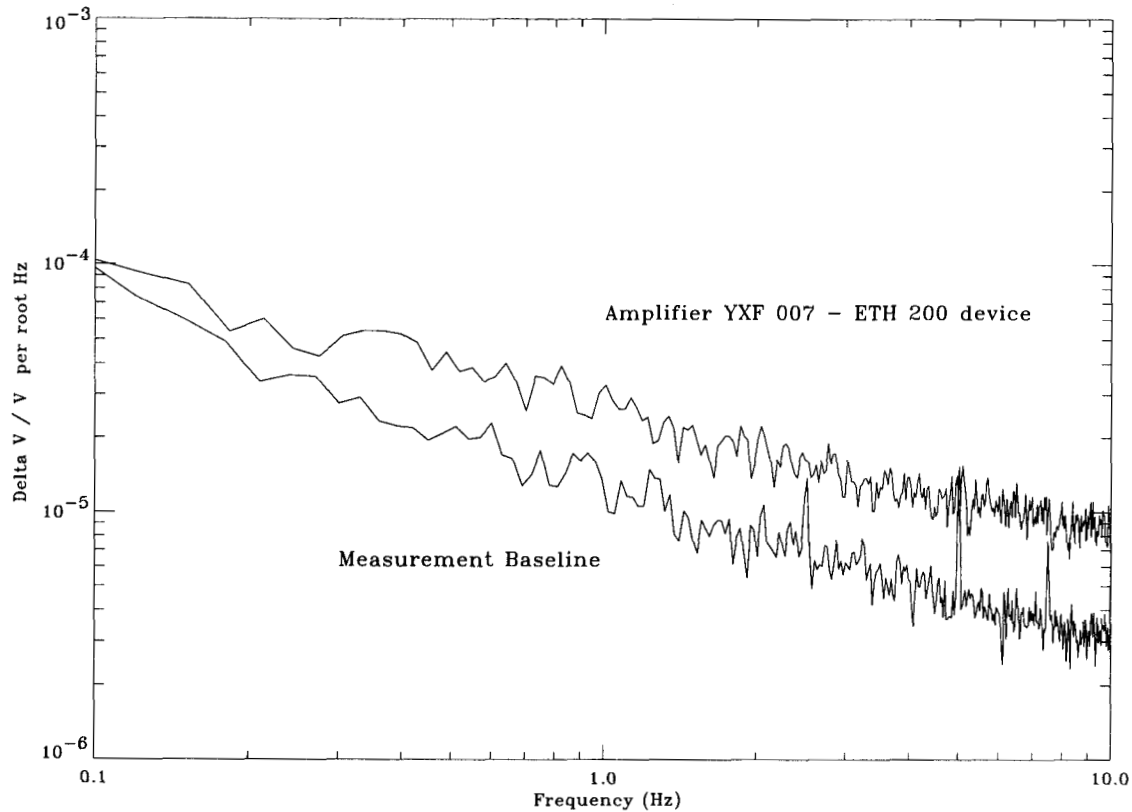


Figure 3. Measurement of amplifier gain fluctuations. The upper curve is the fluctuation level for a two-stage amplifier built with ETH 160 micron devices.

5. CONCLUSION

Wide bandwidth observations with an instrument that possesses $1/f$ type gain fluctuations are possible, but special attention must be paid to the chopping speed, the line width of interest and the level of fluctuation. For the IF amplifiers for HIFI, a slow chop suffices for moderately wide lines. For full continuum sensitivity, however, a chopping speed in excess of 5-7 Hz is probably necessary. A somewhat lower chopping speed would still provide useful information, although at somewhat degraded sensitivity.

ACKNOWLEDGMENTS

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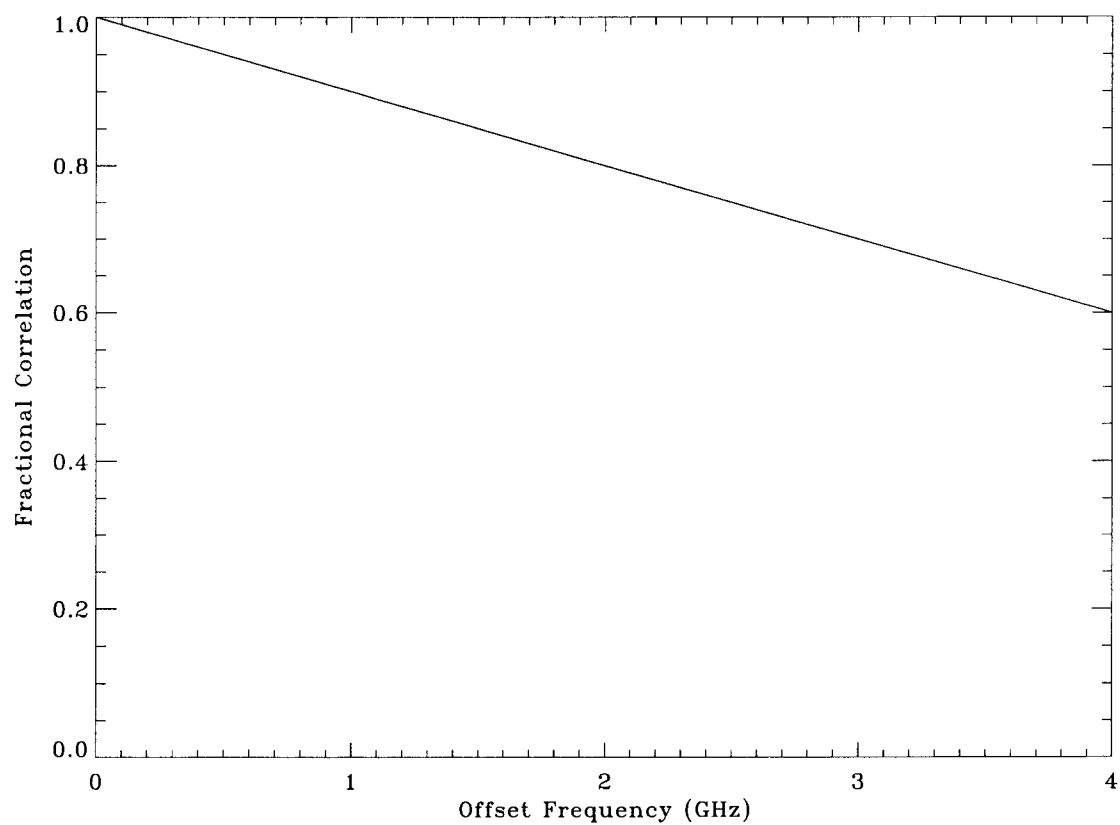


Figure 4. Fractional amplifier gain fluctuation correlation vs. offset frequency used in simulation.

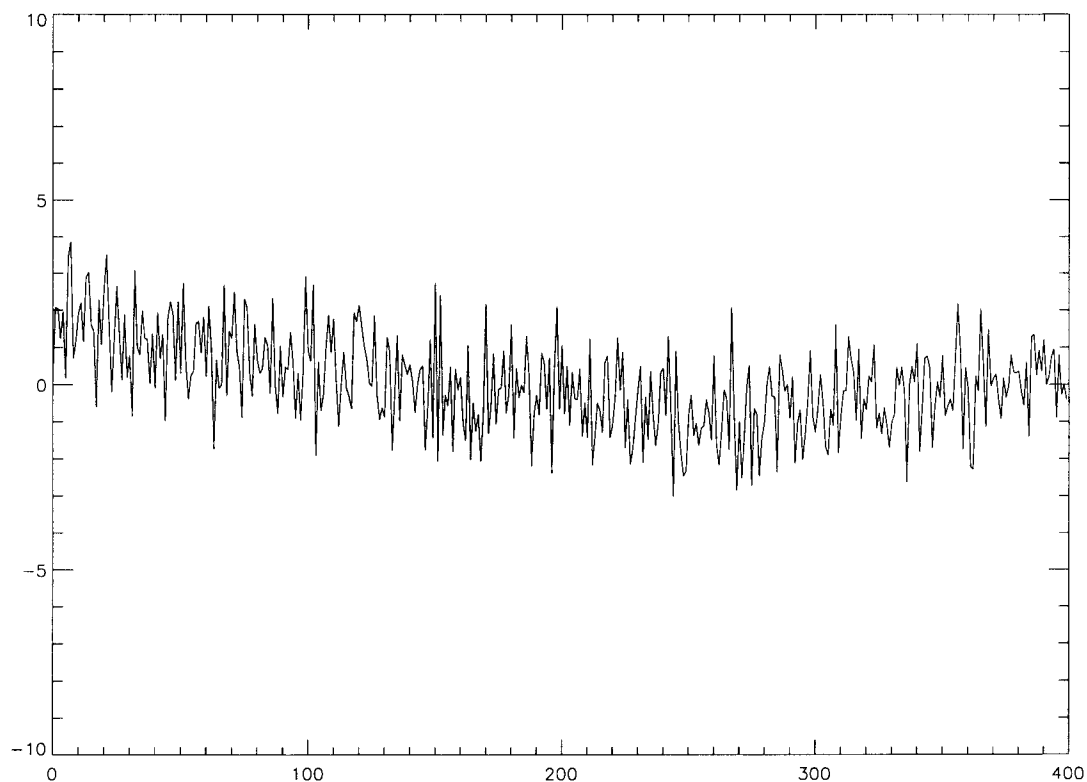


Figure 5. Sample spectrum of wide bandwidth observation with $1/f$ contribution from the IF amplifier. A spectrum has been simulated assuming that there is no source signal and that the gain fluctuation noise from the IF amplifier has a correlation function described in Fig. 4. A gain fluctuation level consistent with the measurements described earlier was used. The resulting structure in the spectrum is due to these gain fluctuations.

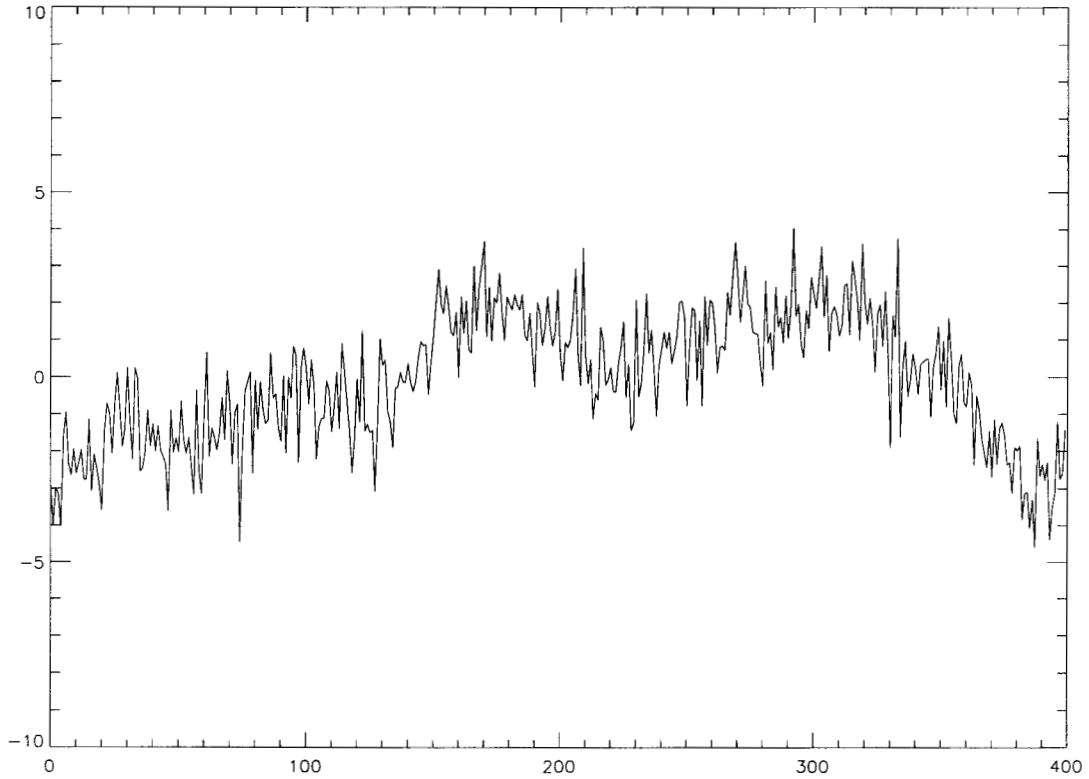


Figure 6. Sample spectrum of wide bandwidth observation with a much larger $1/f$ contribution from the IF amplifier. A spectrum similar to that in the previous figure has been simulated, but now with the assumption that the chopping speed is much slower, and therefore the $1/f$ contribution is larger relative to the white noise. Again, it is assumed that the IF amplifier has a correlation function described in Fig. 4. A gain fluctuation level consistent with the measurements described earlier was used. The resulting structure in the spectrum is due to these gain fluctuations, but is now much larger than in the previous figure.